Session: ***The Evolving Heliosphere over the Solar Cycle and Its Interaction with the Local Interstellar Medium***

Poster: SH51D-2537

Solar wind structure out of ecliptic plane over solar cycles

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Motivation:

The **solar wind** (SW), a stream of plasma continuously emitted from the Sun, governs the environment in the Solar System and forms the **heliosphere**, a *bubble* around the Sun in the Local Interstellar Medium (LISM). The **heliosphere interacts with the LISM** and **new populations of particles** are created. Some of them reach close distances to the Sun and can be **detected by instruments at 1 au**. The **out-of-ecliptic structure of the SW** needs to be taken into account to **interpret the measurements**.

Aims:

- solar wind **speed** and **density** at 1 au
- solar wind **out of the ecliptic plane** from North pole to South pole
- **homogeneous** and **continues** time series
- resolution in time at Carrington rotation period
- time span of a few **solar cycles**

Methods:

- solar wind speed from **interplanetary scintillation (IPS) observations from ISEE** (1985-2016, see Fig. 3)
- SW speed reconstruction following methods described by **Sokół et al. 2015**
- SW density calculated with the use of **solar wind latitudinal invariants**
- **extrapolation** backwards to 1977 and forwards to 2017.5 based on singular spectrum analysis *(preliminary results)*

Sokół, J.M., Swaczyna, P., Bzowski, M., Tokumaru, M. – 2015, *Reconstruction of helio-latitudinal structure of the solar wind proton speed and density*, Solar Phys. 290, pp 2589-2615, doi:10.1007/s11207-015-0800-2

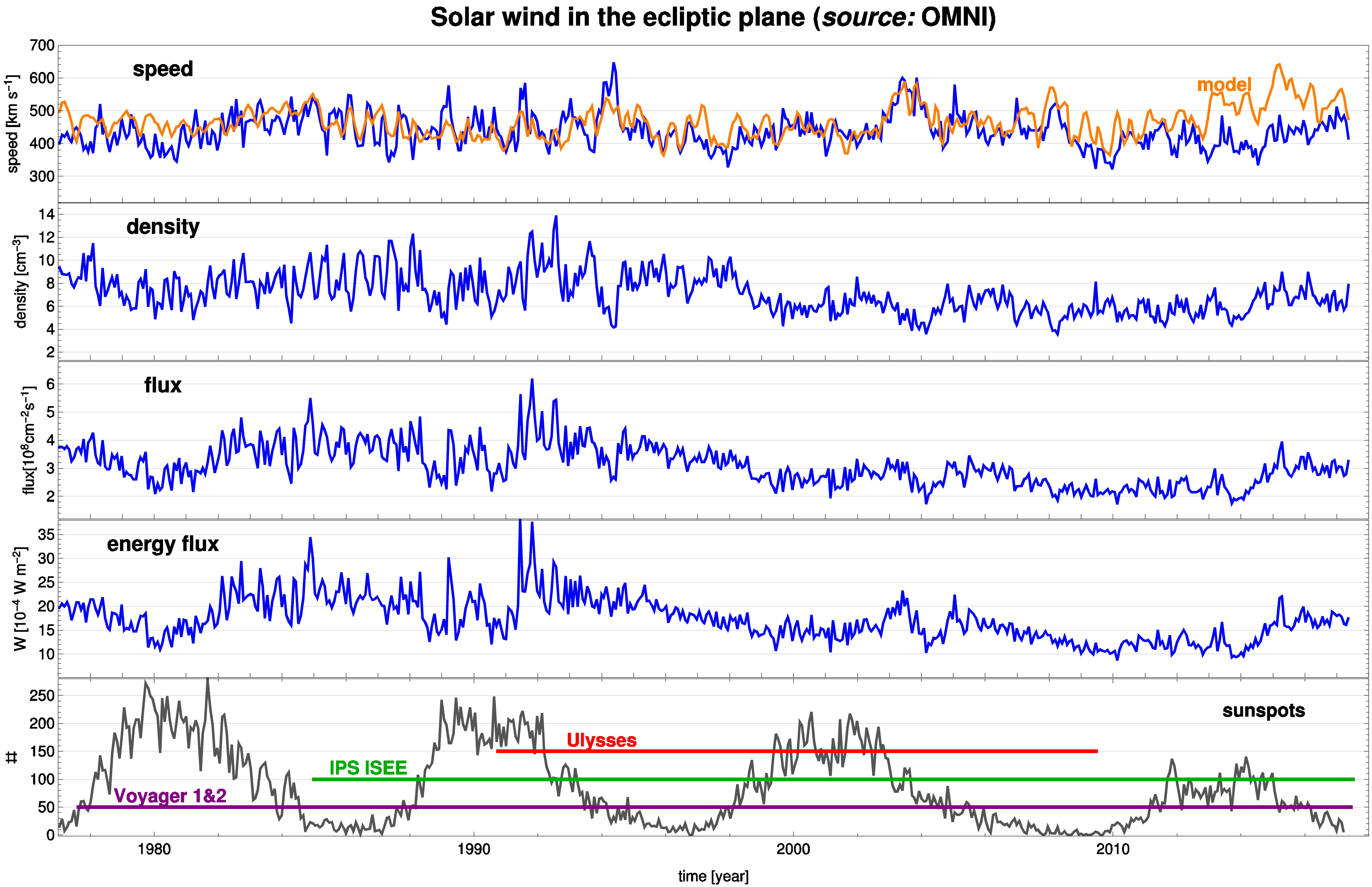


Figure 1: Solar wind parameters at 1 au measured in-situ by in-ecliptic instruments collected by OMNI database (blue line). ***Top panel:*** orange line presents the solar wind at Earth heliographic latitude obtained from the model based on ISEE IPS observations of the solar wind speed. **Bottom panel:** sunspot number (SILSO) together with lifespan of Voyager and Ulysses missions and availability of IPS ISEE observations of the solar wind.

Scaling function for SW speed:

$$f(t,\phi)=\tfrac{1}{2}(\rho(t)-1)\cos(2\phi+\omega(t))+\tfrac{1}{2}(\rho(t)+1)$$

ϕ - heliographic latitude

$\rho(t)$ - ratio of solar wind speed IPS/OMNI

$\omega(t)$ - Earth's heliographic latitude

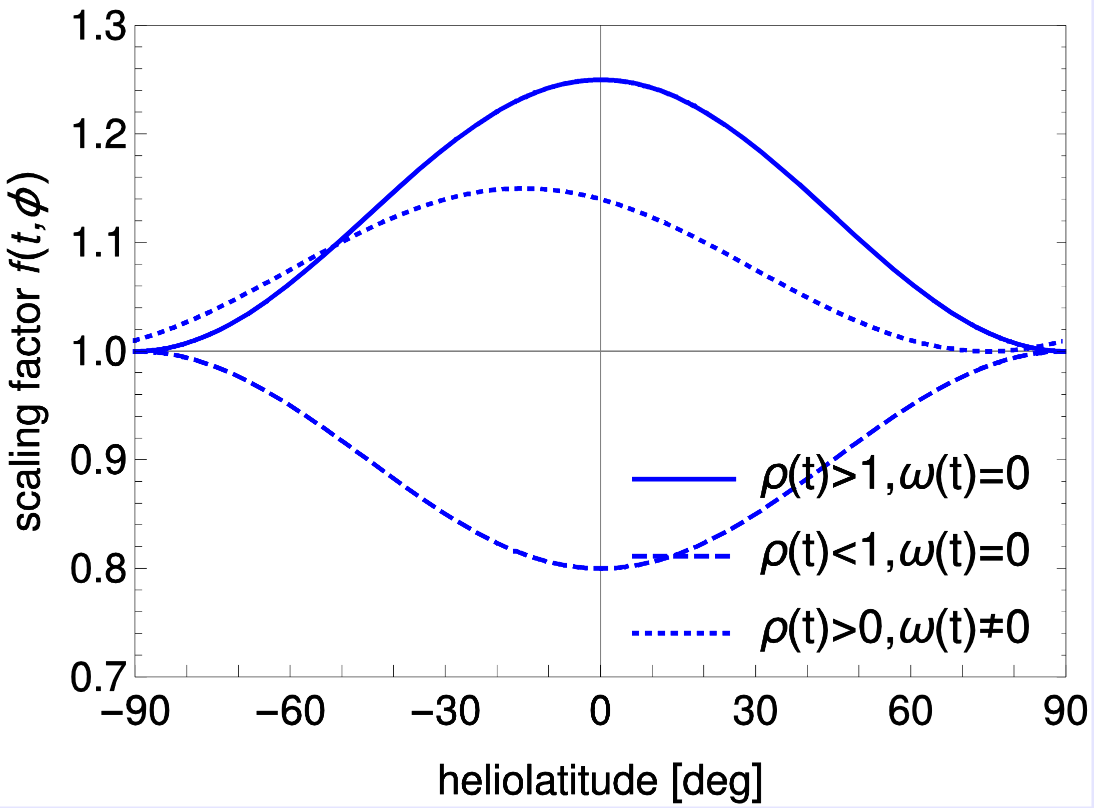


Figure 2: Function to scale the IPS SW speed to the OMNI values in the ecliptic plane with an assumption that the discrepancy between these two data sources decreases with increasing latitude (see top panel Fig.1).

The final solar wind speed in the model:

$$V_{\mathrm{model}}(t,\phi)=V_{IPS}(t,\phi)/\ f(t,\phi)$$

Density calculated from speed using SW latitudinal invariant:

$$W=n_{\mathrm{p}}(m_{\mathrm{p}}+\xi_{\alpha}m_{\alpha})V\left(\frac{1}{2}V^{2}+G\frac{M_{\odot}}{R_{\odot}}\right)$$

W - solar wind advection energy flux (LeChat et al. 2012)

n_p - SW proton density

V - SW proton speed

m_p - mass of the proton

m_α - mass of the α-particle

ξ_α - abundance of α-particle in the SW

G - gravitational constant

See Fig. 1, fourth panel, for the time series of W calculated based on speed and density from OMNI database.

Le Chat, G., Issautier, K., Meyer-Vernet, N. – 2012, *The solar wind energy flux*, Solar Phys. 279, pp 197-205, doi:10.1007/s11207-012-9967-y

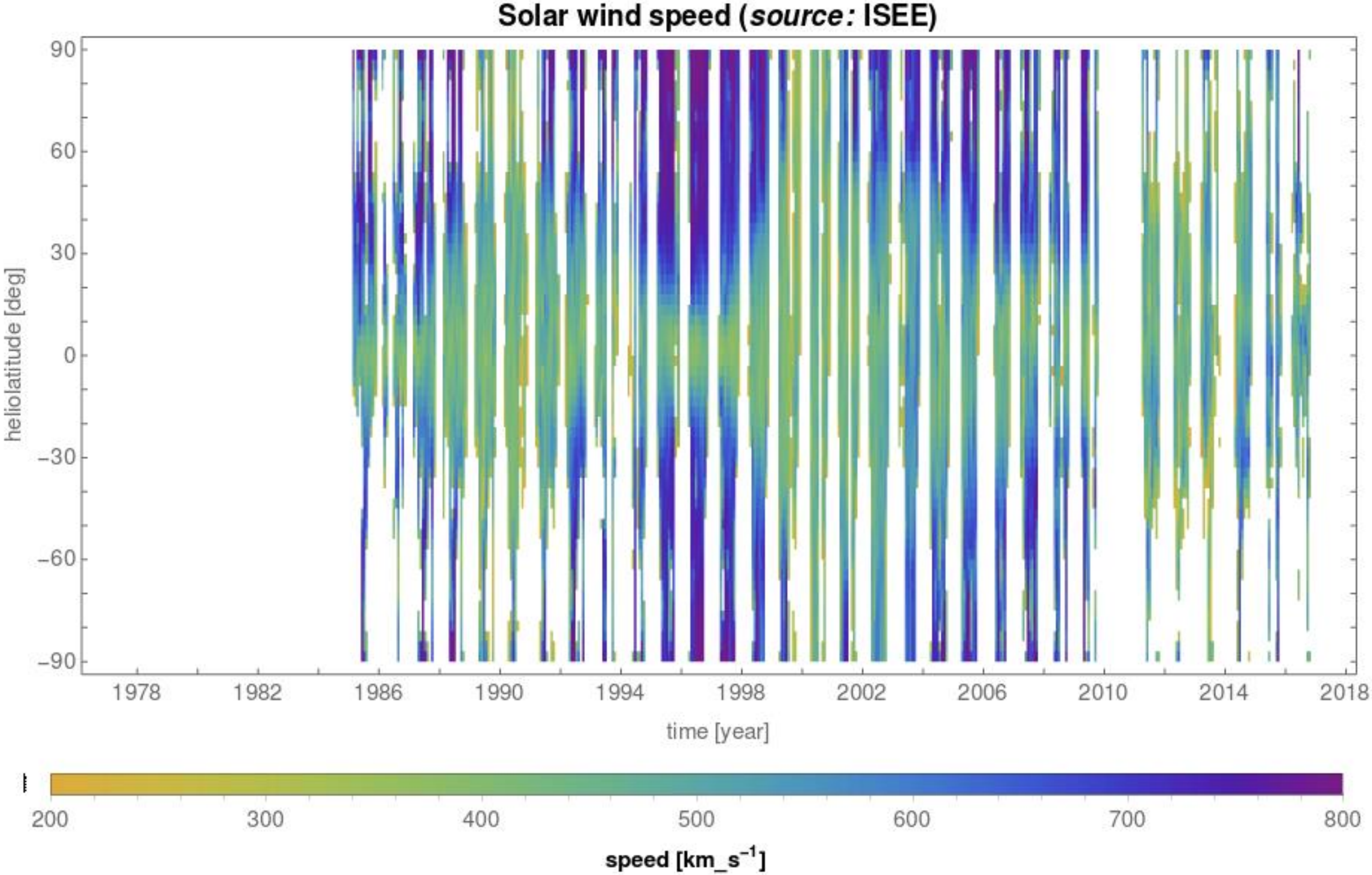


Figure 3: SW speed obtained from the computer assisted tomography of the IPS observations of radio sources performed by the ISEE (Nagoya University, Nagoya, Japan). Regular observations of the latitudinal structure of the SW are made using multi-station observation method, conducted from 1985 with operational breaks of a few months each year and inhomogeneous latitudinal coverage due to the distribution of radio sources in the sky. In this study we assume an instantaneous propagation of the SW with distance.

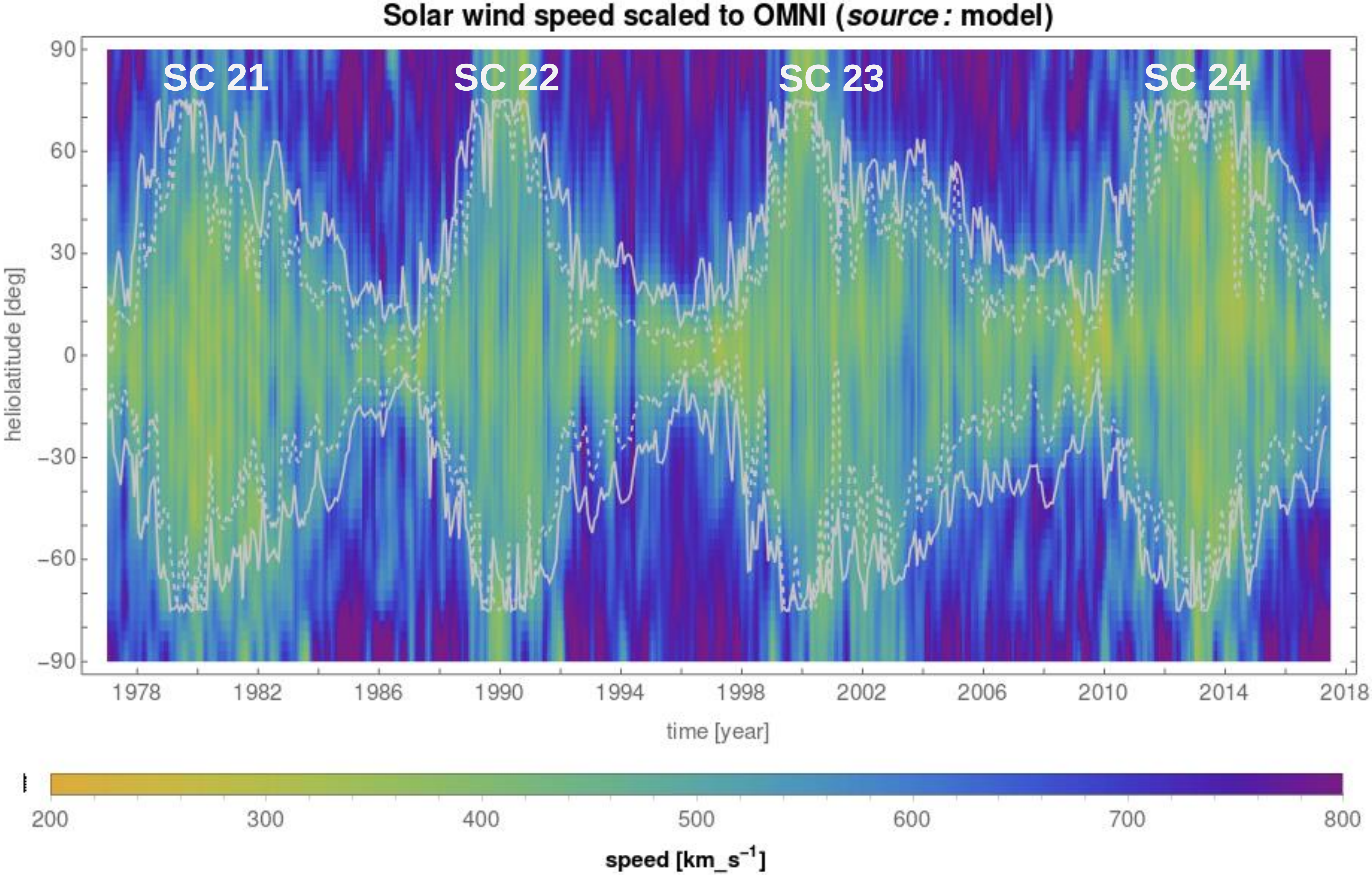


Figure 4: Evolution of the SW proton speed as a function of heliolatitude reconstructed from the IPS data with spatial and temporal gaps from 1985 to 2016 filled using methods described by Sokół et al. 2015 and extrapolated backward to 1977 and forward to 2017.5 with the use of SSA. ***Gray lines:*** computed tilt angle of the heliospheric current sheet (radial and classic model, dashed and solid, respectively / source: The Wilcox Observatory).

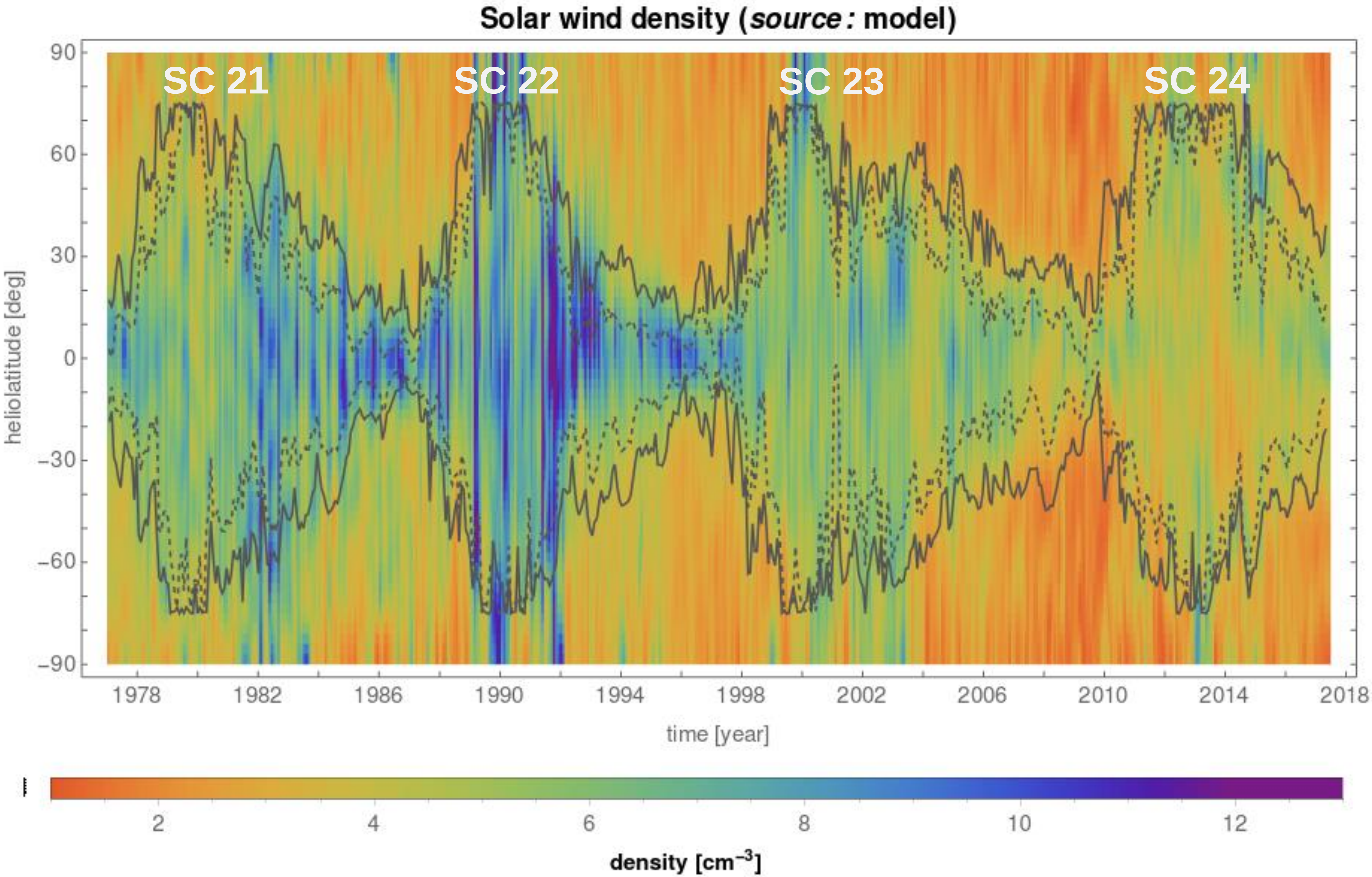


Figure 5: Evolution of the SW proton density at 1 au as a function of heliolatitude calculated from the solar wind speed and the solar wind latitudinal invariant *W* (see Sokół et al. 2015). ***Gray lines:*** computed tilt angle of the heliospheric current sheet (radial and classic model, dashed and solid, respectively / source: The Wilcox Observatory).

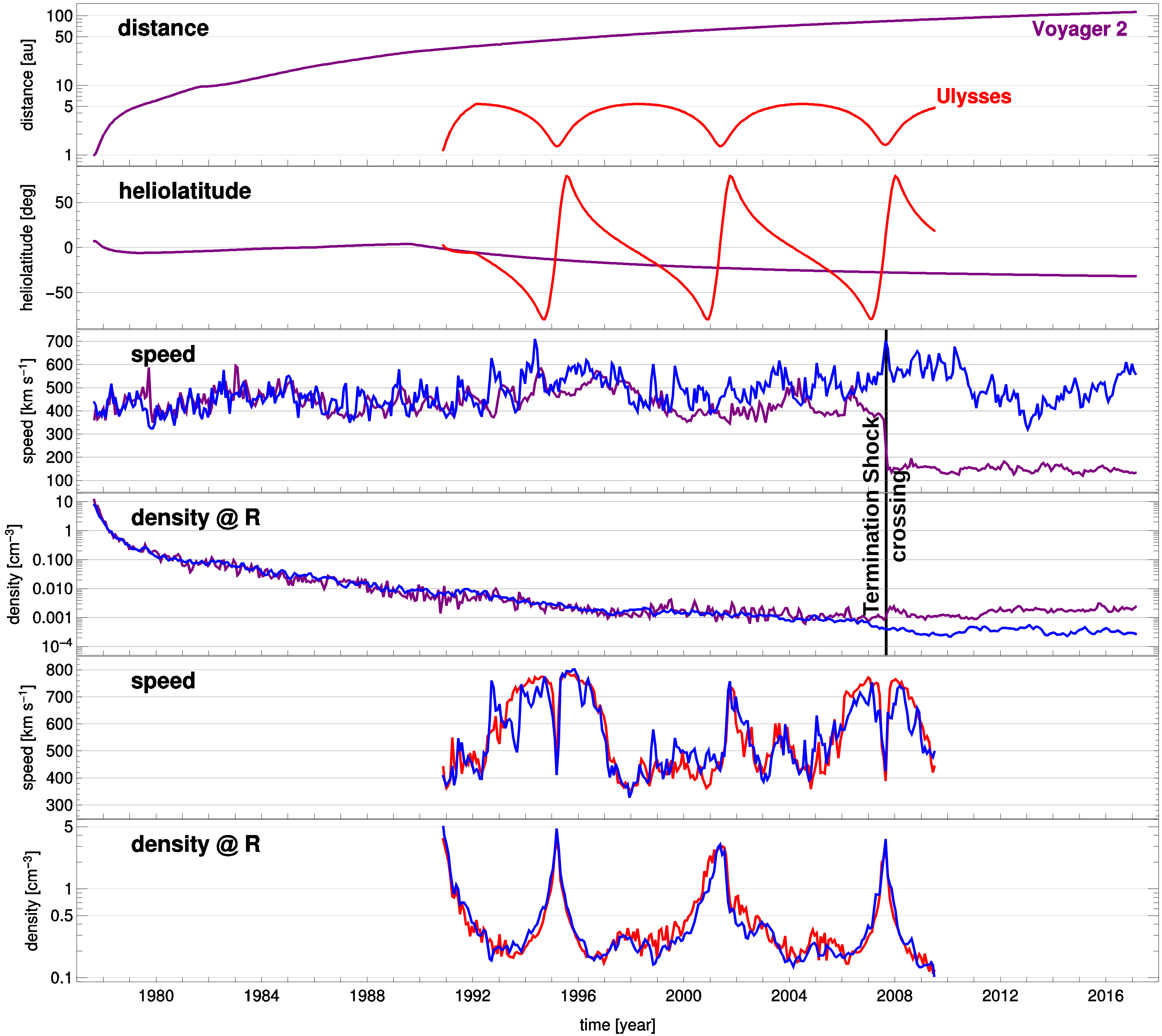
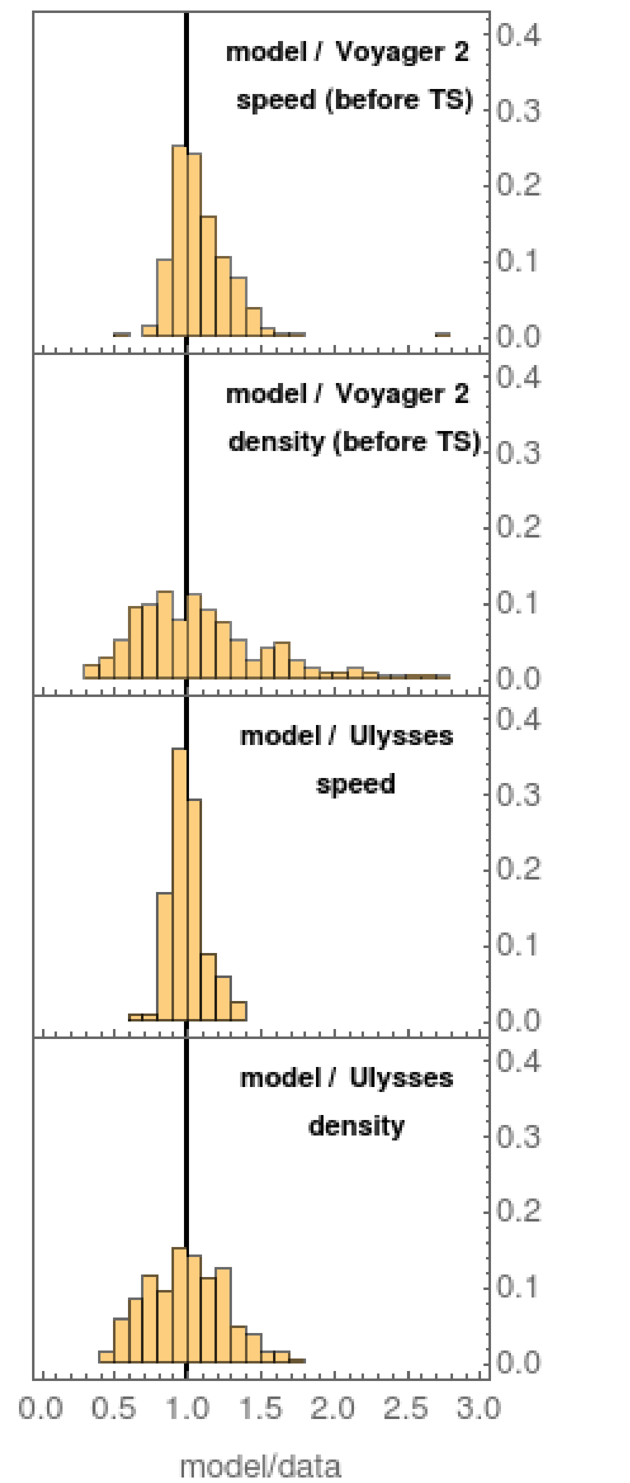


Figure 6:
Right: Comparison of model results with *Ulysses* and *Voyager 2* measurements for Carrington rotation averages of solar wind parameters.
Left bottom: Normalized histograms of model/data ratios.



Summary and conclusions

- Evolution of the solar wind speed and density as a function of heliolatitude is needed for modeling of the heliosphere and correct interpretation of heliospheric measurements.
- In-situ in-ecliptic SW measurements are continuously available from 1963.
- In-situ out-of-ecliptic SW measurements available only from Ulysses (1990-2009).
- Remote, ground-based observations of the solar wind speed by the interplanetary scintillations available from 1985 (ISEE, Japan).
- However, the IPS SW speed diverges from the in-ecliptic in-situ measurements from 2011.
- We have **refined the *Sokół et al. 2015* model** of the reconstruction of the latitudinal evolution of the solar wind by: (1) extending the data set to the end of 2016, (2) introducing an *ad hoc* scaling function, (3) extrapolating backwards in time to the launch of Voyager and forwards to 2017.5.
- The model results show that **the evolution of the slow solar wind range in heliolatitude compares well with the tilt angle of the heliospheric current sheet**.
- We propose **a simple method to extrapolate the latitudinal structure of the solar wind in time** based on singular spectrum analysis.
- The model **reproduces the Ulysses and Voyager solar wind speed measurements reasonably well** (about 25% accuracy), however density is reconstructed with a lower accuracy.

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